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BIOLOGICAL AND CHEMICAL ASPECTS OF ORGANIC WASTE LAGOONS

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Cincinnati, Ohio

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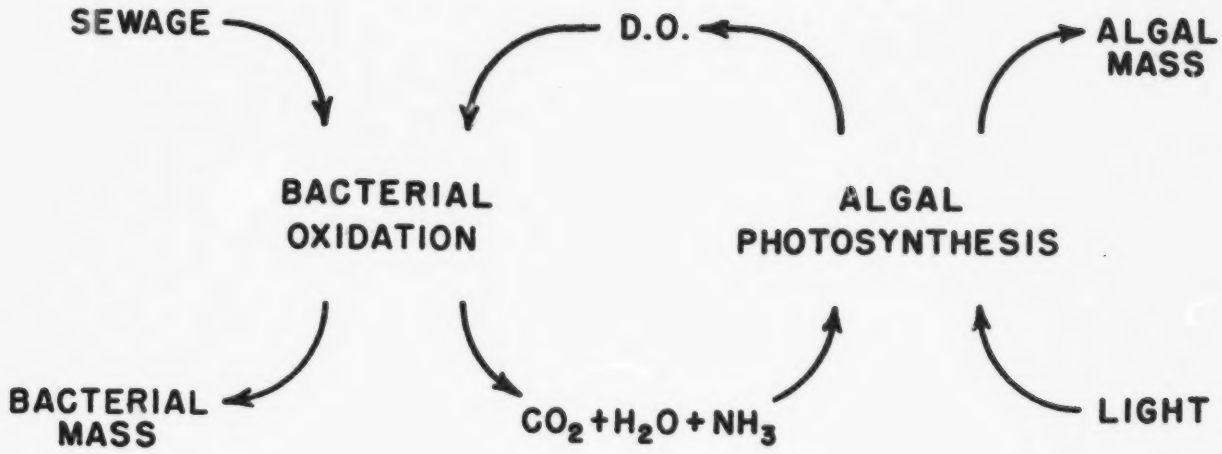
Introduction

The use of lagoons for waste disposal has received wide attention in recent years (1-21). Commonly, such facilities are referred to under a variety of almost synonymous names: cannery and sewage lagoons; oxidation, sewage, and waste stabilization ponds; and settling, retention, storage, and regulating basins. They are used increasingly by municipalities and institutions to treat sewage. During the third quarter of 1955, contracts were let by municipalities for construction of 24 new ones. They likewise have been found useful by a wide variety of industries such as those engaged in food processing, pulp and paper making, leather tanning, petroleum production and processing, ore refining, metal working, and chemical and synthetic fiber production. Recently, interest has been shown in the possibility of using them for removing radioactive waste (22), reclaiming nutrients in the form of algae (23), or preventing nutrient losses to surface waters (24).

In the use of such facilities the immediate objectives may vary considerably but usually include one or more of the following: (a) stabilization of organic matter, (b) destruction of sewage bacteria, (c) storage for controlled discharge under more suitable stream conditions, (d) re-regulation for continuous discharge of intermittent wastes, and (e) separation of suspended or dissolved solids. The present discussion will emphasize the chemical and biological interactions as they occur in ponds used for treatment of municipal sewage. Because the stabilization mechanism is fundamentally the same in cannery waste lagoons, the material will generally apply to them also.

Mechanisms of the Stabilization Process (Fig. 1)

Reduced to simplest terms, the stabilization process is a mutually beneficial interaction between bacteria and algae which, in combination, cause the objectionable characteristics of sewage or other wastes to disappear. Toward this accomplishment, digestive and oxidative activities of bacteria stabilize organic matter and simultaneously produce carbon dioxide, ammonia, and other nutrients needed by the algae, which, through photosynthesis, liberate excess oxygen that helps to maintain an aerobic system. The overall process causes a conversion of relatively unstable organic matter to a more stable algal mass.



STABILIZATION MECHANISM

Fig. 1

A. Sources of Oxygen

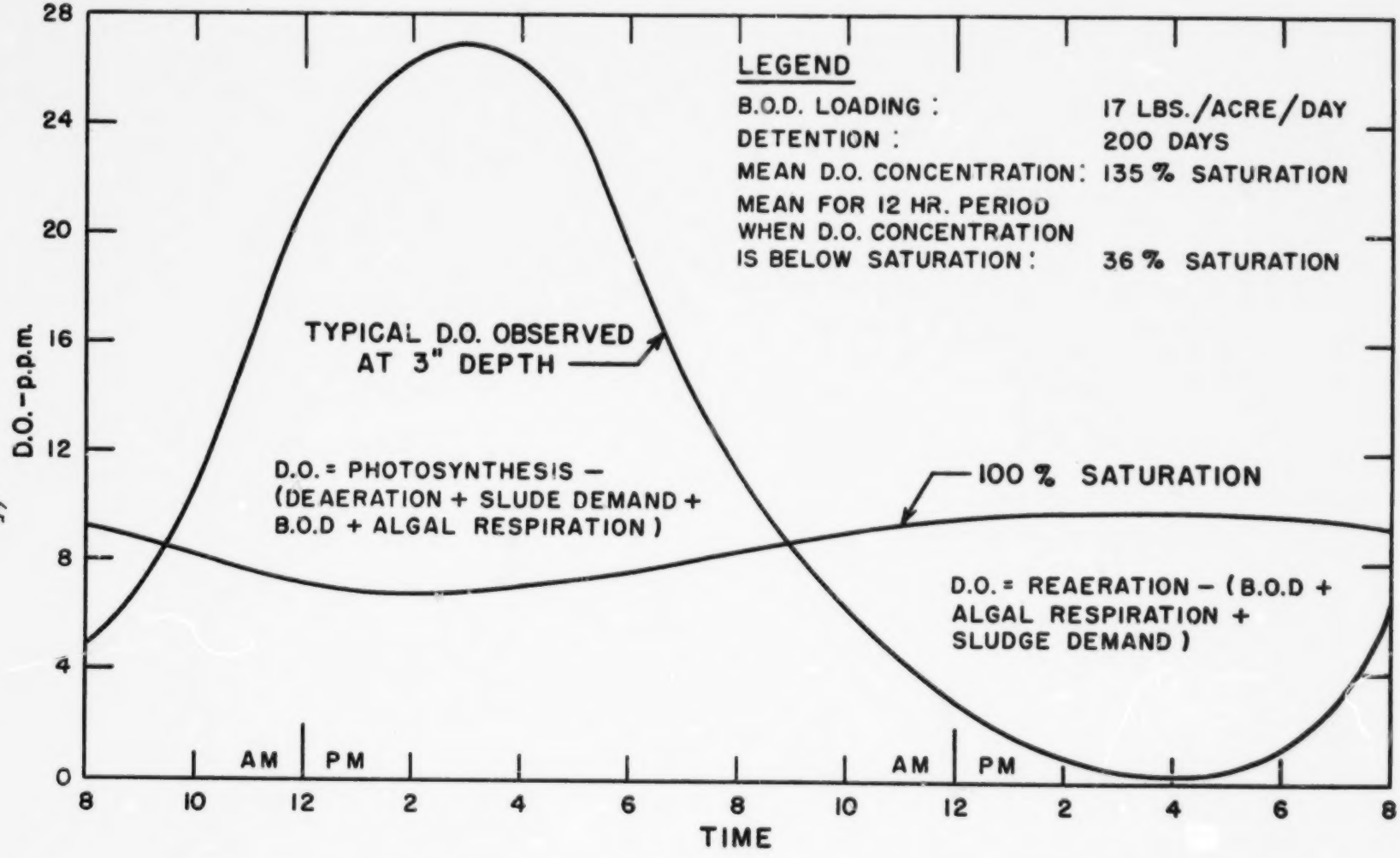
Sustained operation of the stabilization process free of objectionable odors depends upon a ready supply of oxygen. In ponds, oxygen becomes available from three principal sources, the atmosphere by surface aeration, algal photosynthesis, and chemical compounds such as nitrates, sulfates and phosphates. These sources come into play with varying intensity depending upon oxygen conditions that prevail at the moment.

Ponds are believed by some workers (12) to vary considerably in the principal mechanism by which oxygen is supplied. In ponds designated Type I, which have detention periods of from three weeks to six months or more, surface aeration is considered most important. In contrast, photosynthesis is believed to be the major source for Type II ponds, which have detention of less than one week. Distinction between these two types is not always clear cut, and considerable overlapping of oxygenation mechanism is to be expected.

Ponds used to treat raw sewage in the northern plains area do not seem to fit either classification. When loaded at about 17 pounds of Biochemical Oxygen Demand (B.O.D.) per acre per day, and having a detention period of about 200 days, these ponds have a dissolved oxygen concentration typically above saturation for most of the daylight period. In fact, concentrations between 30 and 40 parts per million (ppm) are not unusual. Such high oxygen levels originate only in rapid photosynthesis, and gaseous exchange at the surface at such times results in a loss of oxygen to the atmosphere by deaeration, frequently in the form of visible bubbles.

Contribution of oxygen by surface aeration can occur only when the concentration is less than saturation. Such levels have been found to occur typically between 9 p.m. and 9 a.m., but maximum aeration rate would occur between 3 a.m. and 5 a.m., when dissolved oxygen concentration is lowest. This relationship is shown in idealized graphic form in Fig. 2. Although not representing a specific pond, the magnitudes shown reflect typical observations.

At the loading indicated, 17 pounds of oxygen must be supplied per acre per day to satisfy demand. According to Imhoff and Fair (25), surface aeration in a small pond such as this, having an average deficit of 64 per cent of saturation (or dissolved oxygen of 36 per cent saturation) may contribute in the neighborhood of 8 or 9 pounds of oxygen per acre per day. However, because an oxygen deficit occurs for only 12 hours of the day, surface absorption is estimated to be roughly 4 pounds. From this it appears probable that surface aeration furnishes only about one-fourth of the oxygen needed to satisfy the B.O.D.



SURFACE AERATION VS. PHOTOSYNTHETIC OXYGEN PRODUCTION

Fig. 2

Sodium nitrate serves as a source of oxygen for bacterial respiration, replacing dissolved oxygen as a source under certain circumstances. Intermolecular respiration of this kind involving nitrate is believed to go into action only after free dissolved oxygen has been completely used. Why sodium nitrate can serve as a deterrent to odor formation is shown by the order in which oxygen-bearing compounds enter the respiratory process. As each successively preferred source of oxygen is exhausted, dissolved oxygen, nitrate, nitrite, sulfate, and phosphate are attacked in sequence. Involvement of the sulfate molecule, however, leads to formation of hydrogen sulfide.

Use of sodium nitrate typically leads to formation of ammonia and maintenance of high pH, both of which enhance algal production and resulting higher oxygen levels.

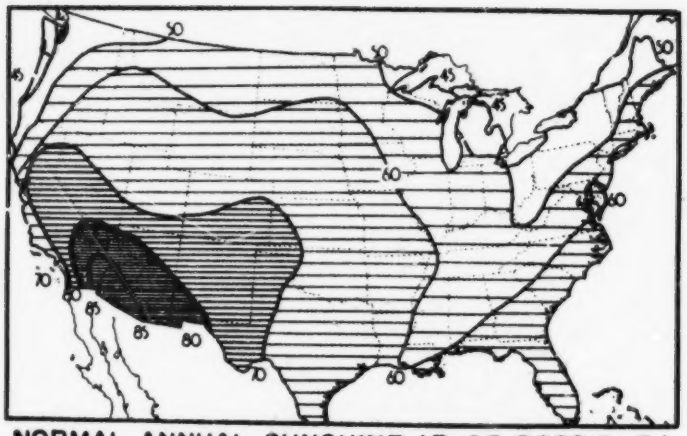
B. Light and Light Penetration

Because of the role of photosynthesis in production of oxygen, light is indispensable to the stabilization process that has been described. Three different but related considerations are involved in the importance of light and help to determine how well the pond operates and the area and depth needed.

First, there is the regional variation in annual solar radiation, which is governed by latitude, elevation, and cloud cover. As shown in Fig. 3, most of Wisconsin, Minnesota, and North Dakota are in an area where normal annual sunshine is about 50 per cent of the possible total; to the east it is only 45 per cent; to the southwest 60 per cent or more (29). The solar radiation factor can be considered in pond design equations (7), but certainly is recognized also in rule-of-thumb criteria used in various states.

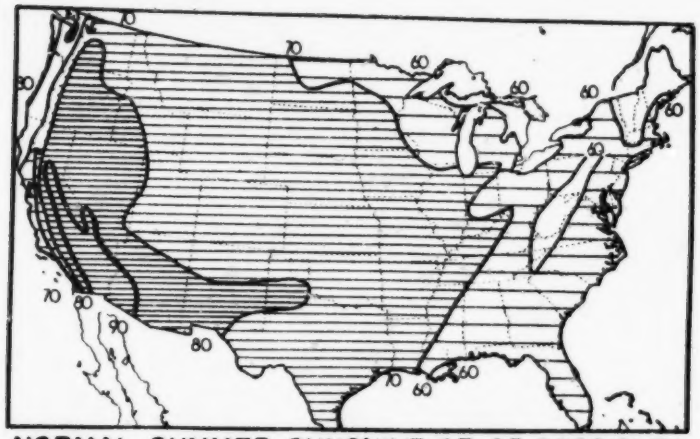
Second, seasonal changes in the amount of daily solar radiation may vary locally by a factor of 3 or more (29). Fig. 4 shows that normal summer sunshine in Wisconsin is 60 per cent of that possible, an increase of 20 per cent over the normal winter condition (Fig. 5). Expressed in langleys (gm.-cal./cm^2) per day, it varies from about 150 on January 21 to about 550 on June 21. The amount of solar radiation, which is governed both by light intensity and length of day, helps to determine seasonal rates of photosynthesis and the related oxygen production.

The third consideration in which light is principally concerned is the extent to which the pond volume participates in oxygen production. It relates, therefore, to depth of light penetration through the pond content and hence influences determination of the desirable pond depth.



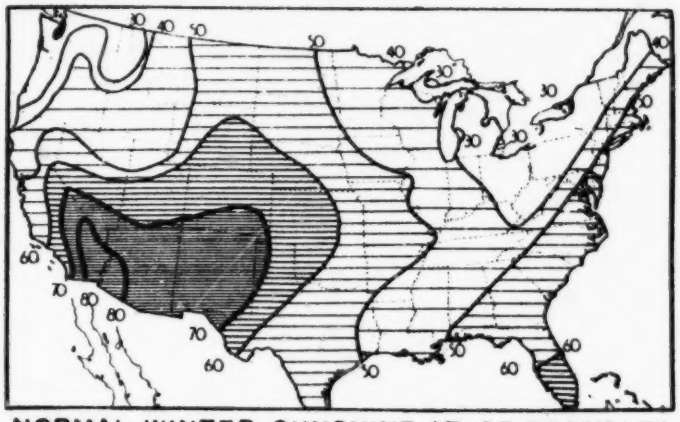
NORMAL ANNUAL SUNSHINE (% OF POSSIBLE)

Fig. 3



NORMAL SUMMER SUNSHINE (% OF POSSIBLE)

Fig. 4



NORMAL WINTER SUNSHINE (% OF POSSIBLE)

Fig. 5

In Fig. 6, light penetration in three different ponds is plotted as log of the percentage of surface light intensity remaining at the depths indicated. An inverse linear relation of light intensity to depth was observed, as expected from the Beer-Lambert Law for light absorption. Surface losses by reflection increased with surface roughening, but typically were found to be about 30 per cent of the incident light.

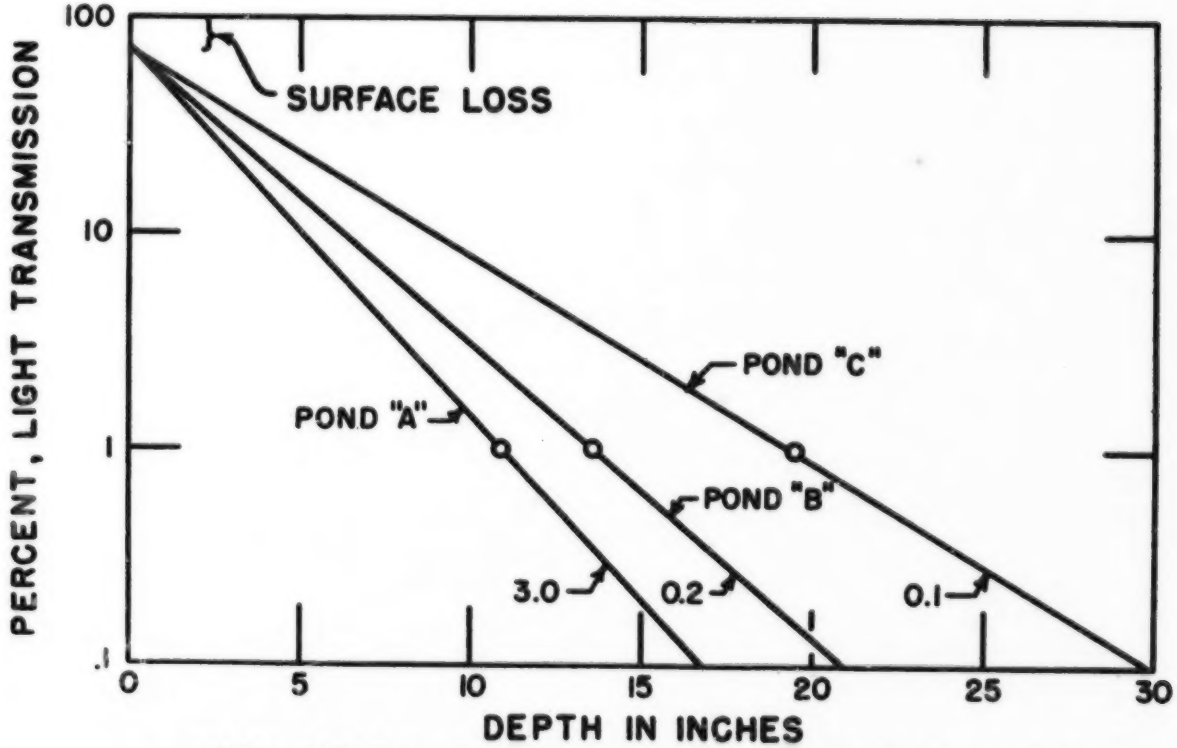
Variation in the light absorbing quality among ponds suggests an individuality which can be expressed as the depth at which only 1 per cent of the surface light remains. For the ponds shown, under summer conditions, these depths are 11, 13.5 and 19.5 inches. During spring, these depths sometimes were less -- in some ponds as little as 2 inches. This was related to density of algal growth. In contrast to this, the depth of 1 per cent light intensity for an artificial lake in the same region was 21 feet.

Variations such as these in light intensity with depth are largely determined by algal density, which varies seasonally and from pond to pond. Much of the light absorption by algae results from the presence of chlorophylls which have strong affinity for the red and blue wave length regions of the spectrum. Fig. 6 shows that light intensity (at a given depth) and concentration of chlorophyll are so related that rapid extinction of light and high chlorophyll A concentration repeatedly occur together. Chlorophyll concentrations in sewage ponds are exceedingly high, reaching 7.3 ppm, in contrast to Lake Mendota (Madison, Wisconsin) with high concentrations in the neighborhood of 0.05 ppm (30).

Although some degree of nonuniformity in vertical distribution of algae in these ponds is not uncommon, concentration in an extremely thin layer has rarely been observed. On one occasion, however, shown in Fig. 7, Euglena cells were concentrated in a 3-inch thick layer 4 inches below the pond surface. Intense absorption of light passing through this area of stratified algae emphasizes the relationship of algal density to rapid extinction of light.

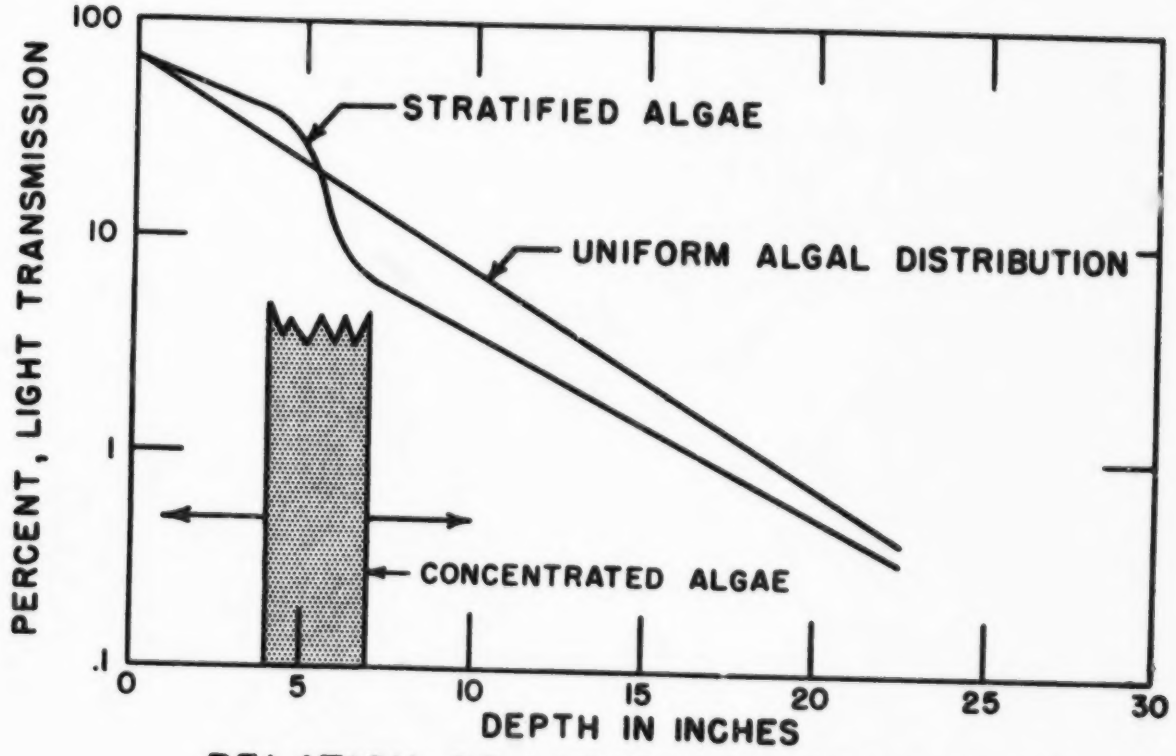
Dissolved oxygen production at different depths has been measured on several ponds by use of light and dark bottle tests. These tests measure the dissolved oxygen change in a pond sample during incubation at selected depths in clear bottles and in others covered with aluminum foil to exclude light. Typical data from one test are shown in Table I.

These data show that the rate of oxygen production from photosynthesis drops off rapidly with depth in a logarithmic fashion somewhat parallel to the extinction of light. It is also evident that in this case oxygen production did not equal the demand at depths greater than 24 inches. If oxygen production were the only consideration, oxygen return for increments of depth beyond 24 inches would have to be carefully weighed in relation to excavation costs.



RELATION OF LIGHT PENETRATION TO CONCENTRATION OF CHLOROPHYLL A (p.p.m.)

Fig. 6



RELATION OF LIGHT PENETRATION TO ALGAL STRATIFICATION

Fig. 7

Table I

DISSOLVED OXYGEN PRODUCTION AT DIFFERENT DEPTHS

During Five-Hour Period
23° C

% SURFACE LIGHT	APPROX. F.C.	DEPTH INCHES	D. O. CHANGE (RESP.) COVERED	D. O. CHANGE (PHOTO) UNCOVERED	OXYGEN PRODUCTION
13	811	10	-2.1	+12.6	14.7
1.6	99.8	24	-2.1	- 0.0	2.1
0.2	12.5	38	-2.0	- 1.4	0.6
0.02	1.25	53	-1.8*	- 1.6	0.2

Determinations were made in triplicate.

* Separate sample.

How deep a pond should be is not fully answerable at the present time. If the objective is to treat raw sewage aerobically, allowable depth would be less than for cannery waste lagoons in which the objectives of storage and nitrate treatment enter into the picture.

C. Temperature

Temperature, whether or not related to other seasonal changes, affects the stabilization process mainly through its influence on the rate of the B.O.D. reaction, including algal respiration, and on the dissolved oxygen saturation value. Relation to oxygen production in photosynthesis must be considered also.

The water temperature of ponds in the northern half of the country can be expected to range from near 0° C under ice to as much as 35° C or more at midsummer. Over this temperature range, the rate at which the ultimate carbonaceous B.O.D. is satisfied changes widely. As shown in Table II, it takes 13 days at 5° C to accomplish what takes only 4 days at 30° C. This rate change is one of several factors that account for lowered wintertime efficiencies noted in ponds used for raw sewage and for cannery wastes.

In lagoons used for treating white water from paperboard mills, allowable loading was found to be a linear function of temperature from 13° C to 30° C (31). In a four-foot lagoon, loading could be increased 1.5 times by raising the temperature from 20° C to 30° C.

During the low temperature period before and immediately after ice cover, photosynthetic production of oxygen alone may be insufficient to meet demands. At these times, the dissolved oxygen saturation value may approach twice the summertime values. As long as ice is not a barrier, surface aeration then assumes greater importance and helps to satisfy the demands exerted.

Laboratory tests have shown that with certain species of Chlorella, which are common green algae, a rise of 10° C may accelerate the photosynthetic rate from 50 to more than 200 per cent (32). A generally similar temperature effect has been found also for algae living under natural conditions (33) (34).

In spite of this, the effect of temperature drop alone on the rate of oxygen production by photosynthesis in waste stabilization ponds cannot be determined readily. Other influences, such as diminishing solar radiation, drop in algal density, and change in species composition occur at the same time. Together, these changes bring about a reduction in the oxygen production rate, so that values of 300 or 400 per cent of saturation, as found in late spring and summer, do not occur in the colder months.

Table II

EFFECT OF TEMPERATURE ON RATE OF B.O.D. SATISFACTION

TEMP. °C	TIME IN DAYS* FOR 90% B.O.D. SATISFACTION
5	13.1
10	10.4
15	8.3
20	6.7
25	5.3
30	4.2

* $k_1 = 0.15$ at 20° C

$k_T = k_{20} \times 1.047^{(T-20)}$

Based on ultimate first stage B.O.D.

D. Diurnal Fluctuations

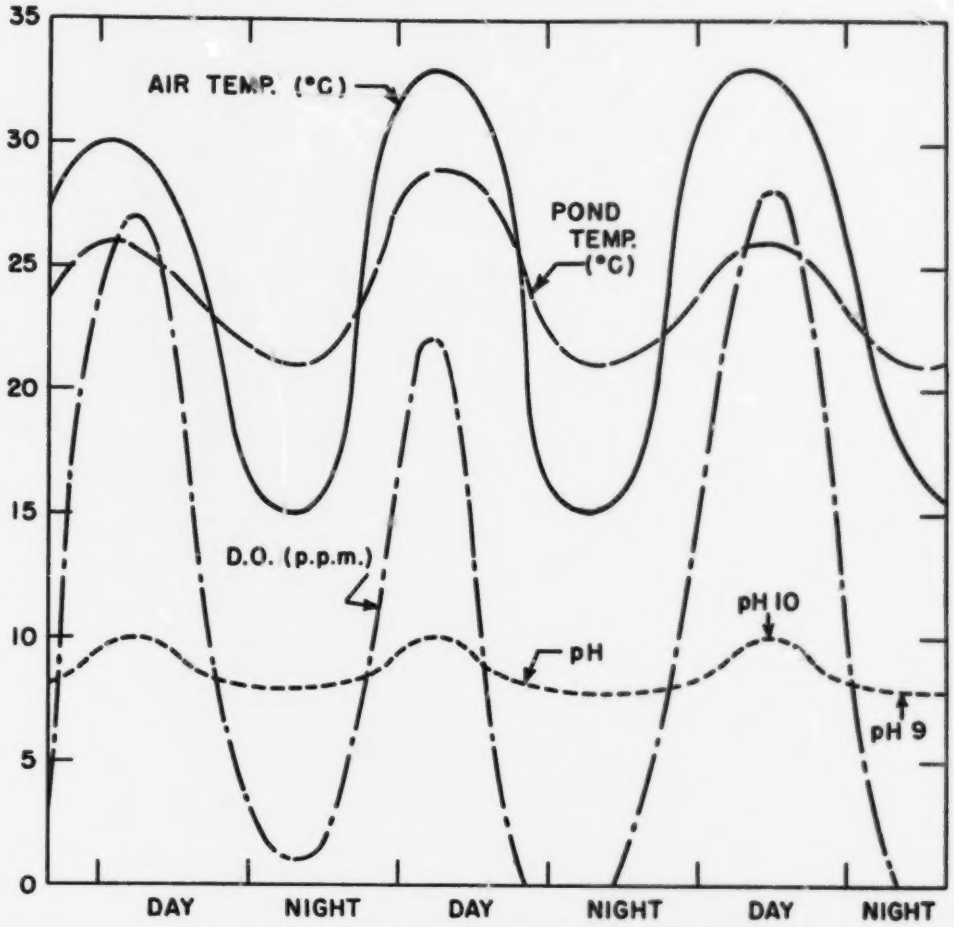
Daily changes in solar radiation and temperature bring about a recurring pattern in pond temperature, oxygen concentration, pH, and certain other characteristics. This repeated diurnal pattern is shown in idealized form in Fig. 8.

Fluctuations in air temperature that are keyed to daylight warming by the sun and cooling after sunset, cause corresponding changes of lesser magnitude in the pond. The shallower the pond, the more closely its temperature follows that of the air. The graph represents the response in a 4-foot deep pond.

The daily highs and lows in dissolved oxygen concentration result mainly from changing light intensity. Moreover, the magnitude of the peak for a given day is largely governed by degree of sky cover and extent of deaeration. Diurnal fluctuations in pH between 9 and 10 are related to utilization of CO_2 in photosynthesis. Although algae may use free CO_2, it is more likely that the bulk of the CO_2 is obtained by breaking down bicarbonates with resulting formation of monocarbonates.

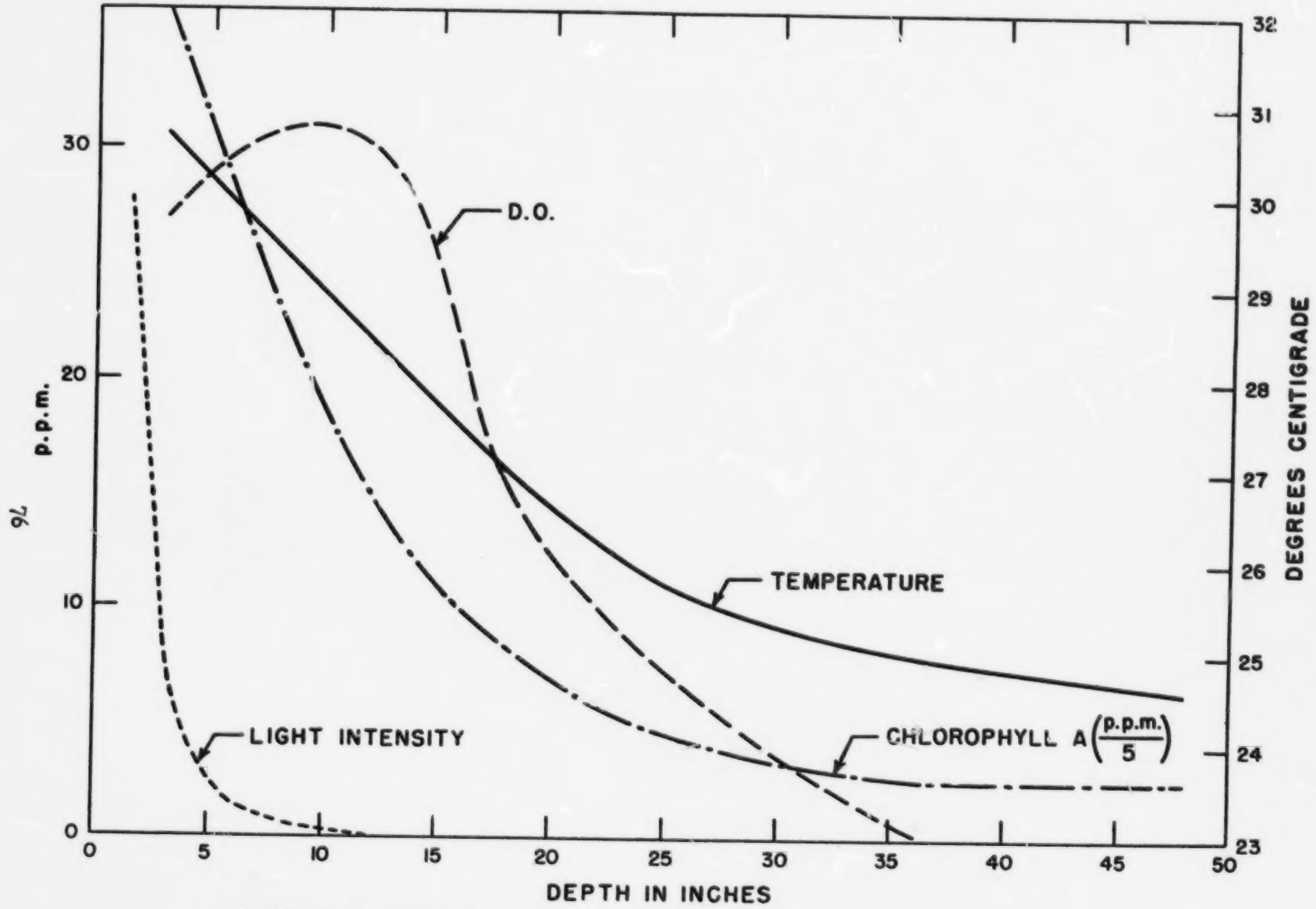
It seems quite obvious that the dissolved oxygen economy of waste stabilization ponds during open water seasons consists of closely spaced periods of great surplus and great poverty. Daytime concentrations may exceed 400 per cent of saturation, and breaking bubbles at the surface may actually give a sizzling sound. At night, only 12 hours later, it is not unusual for the dissolved oxygen content to approach or reach zero. Based solely upon the ratio of oxygen use to oxygen production, the stabilization mechanism leaves much to be desired in the way of efficiency. Various mechanisms by which better oxygen utilization can be obtained need to be explored.

Scrutiny of the daily cycles of temperature and dissolved oxygen (D.O.) tells only a part of the story of what happens in the pond. On calm sunny days, forces are set in motion at daybreak that lead to sharp vertical gradients in temperature, dissolved oxygen, and algal distribution as shown by chlorophyll A (Fig. 9). The exact sequence of events is not known, and considerable overlap may occur, but it seems likely that the algae start off the process by concentrating toward the surface in response to light. The temperature gradient may result from the heat-absorbing properties of the concentrated algae. Algal distribution relative to light intensity, and perhaps temperature also, determines that photosynthetic oxygenation will be greatest somewhere near the surface and essentially absent at the bottom.



DAILY FLUCTUATIONS IN TEMPERATURE AND CHEMICAL QUALITY

Fig. 8



VERTICAL GRADIENTS FORMED ON CALM BRIGHT DAYS

Fig. 9

A lower D.O. concentration at 3 inches than at 10 has been observed repeatedly in gradients of this type. It is believed that this occurs because of the variable relative importance of escape to the atmosphere and hydrodiffusion at the different lagoon depths.

Such striking vertical gradients form readily only during calm sunny weather. Once formed, they may be disrupted easily by wind, heavy rain, and nightfall. Therefore, the pond approaches daylight with a fairly uniform vertical distribution in temperature, dissolved oxygen, and algal density. Because of the alternation between a strong daytime gradient and nighttime uniformity in vertical distribution of algae, the loss of algae by pond overflow follows a fluctuating daily rate.

E. Seasonal Factors

At formation of ice cover, the stabilization process changes in both character and accomplishment. The influence of temperature has already been described. Another striking influence is limitation of light penetration so that photosynthetic oxygen production is less than existing demand, even when algal density is appreciable. This is understandable when ice cover from 9 to 27 inches can reduce light intensity 75 to 99.5 per cent. Surface reaeration is inoperative and photosynthesis impaired tremendously under these conditions. In spite of the slower rate of B.O.D. satisfaction, it is not long before the dissolved oxygen resources are exhausted. Hydrogen sulfide is present throughout the ice cover period and kept from escaping to the atmosphere by the surface barrier.

Studies of cannery lagoons (26) showed that solids are thrown out of solution and suspension as ice cover is being formed. Because some of the precipitated solids do not go back into solution, the supernatant remains relatively clear. This sedimentation may in part account for the extent of B.O.D. reduction noted in sewage ponds in winter.

Concentration of chlorides by freeze-out has been noted. In shallow sewage ponds, where ice volume is proportionately great, chloride concentration may reach three times the open water value; where ice volume is small, the winter increase may not exceed 25 per cent.

At time of the spring melt, ice serves as a source of fairly pure dilution water. Melting begins at the edges and on top, with the surface film well aerated by wind and mixed and circulated into the pond content under the ice. This may help to reduce odor conditions at time of ice melt.

Cannery lagoons and raw sewage ponds, while functioning with the same basic mechanism, differ mainly in the pattern and intensity of loading (Fig. 10). Cannery wastes are produced for only about one-third of the year, but loading is exceedingly high. In lagooning of beet sugar wastes, also, the B.O.D. loading rate greatly exceeds the rate of satisfaction (35). As a result, the amount of B.O.D. remaining at any time during the campaign has been found to be about one-half the amount added. Because of loading patterns such as these, B.O.D. concentration in a cannery lagoon in summer, fall, and winter may be 20 or more times as great as in a pond receiving raw sewage at a lower and more uniform rate.

B.O.D. peaks and the dissolved oxygen pattern in a cannery lagoon correspond to pea pack and corn pack operations. In a raw sewage pond the winter depression of dissolved oxygen and slight elevation of B.O.D. are mainly indicative of winter impairment in oxygen production.

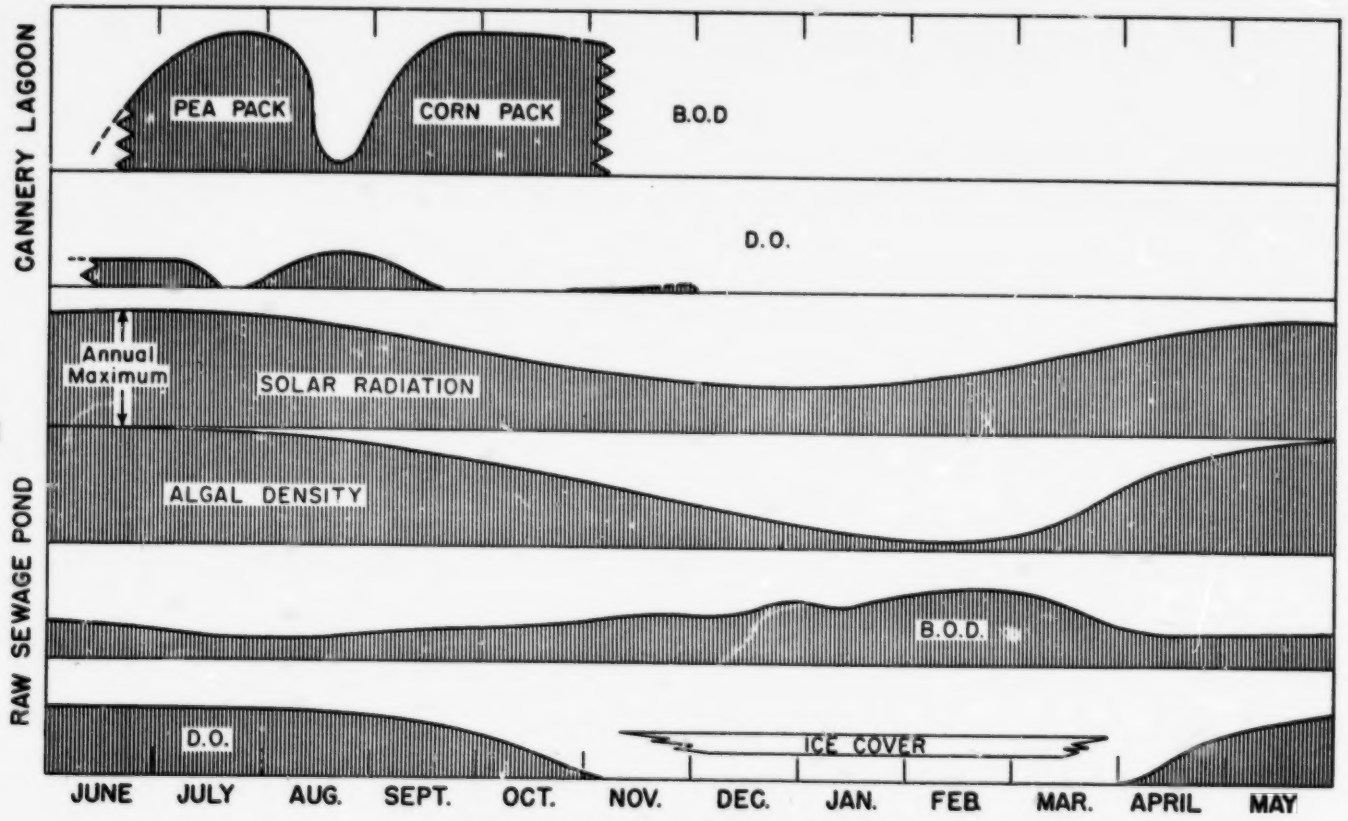
F. Algal Characteristics

The importance of algae in stabilization ponds stems largely from their production of needed oxygen. California pilot plant studies (7) showed an average yield of 1.65 pounds of oxygen for each pound of algae produced. This capacity alone justifies interest in the kinds, seasonal variations, and geographic distribution of the algae concerned.

Systematic studies (36-38) reveal a thread of relationship among different ponds in spite of their striking individualism. Names of certain algae, such as Chlorella, Scenedesmus, Euglena, Ankistrodesmus, Chlamydomonas and Micractinium, come up so frequently as to appear characteristic of this habitat. In ponds used for raw or settled sewage, either Scenedesmus or Chlorella commonly is dominant in winter, but other genera may become more important at other seasons. In cannery waste lagoons also, the dominant alga is usually Chlorella, which tends to increase as the pack progresses and may attain densities of 66 million cells per milliliter (41). Geographic variations in the algal pattern are generally minor, and the families represented by the dominant kinds are essentially the same in all regions that have been studied.

In some industrial waste lagoons, these plankton populations do not develop. In a Minnesota cannery lagoon, purple, non-sulphur bacteria become prominent at some stage (39). In ponding of Kraft liquor, bacteria function without the symbiotic relation with algae (40).

In raw sewage ponds, which normally are loaded at a fairly constant rate, minor fluctuations in the number of different algal species are more likely a response to season than to loading pattern. In cannery and beet sugar waste lagoons, in which loading is



SEASONAL RELATIONS

CANNERY WASTE LAGOON VS. RAW SEWAGE POND

Fig. 10

extremely intense for a fairly short period, the variety of organisms decreases as the season progresses. A loss of 75 per cent of the initial number of species is not uncommon. Observations of several Wisconsin cannery lagoons showed that number of species and B.O.D. loading were inversely related (41).

G. Suitability of the Medium for Algae

All of the elements needed in appreciable quantities for algal growth are present in sewage but not in the proportions usually considered desirable in synthetic culture media (42). Of particular note as components of sewage are nitrogen, phosphorus, potassium, magnesium, and sulphur, some of which frequently are in short supply in natural surface waters. These elements are either in acceptable form in sewage or become assimilable through bacterial action. As one would expect, their presence in sewage reflects assimilation from soil, water, and air of all the elements found in food. Comparison of elemental composition of algae grown in fresh water with those grown in sewage shows that they differ appreciably only in having a lesser percentage of carbon when grown in sewage. Carbon deficiency in the sewage medium is believed to be the cause.

Some industrial wastes, on the other hand, are deficient in one or more of the necessary food elements because of their restricted origin. Nutrient content is inadequate for proper conduct of the B.O.D. test or to support a desirable pond biota. Examples are wastes from pulp, paper, and textile mills, canneries, and petroleum refineries. Recent studies on fortification of nutrient-deficient wastes (43) showed optimum B.O.D. to nitrogen ratios of about 20 to 1. Nitrogen content in sewage is commonly greater than this. Nitrogen and phosphorus deficiencies, which are the most common kinds, are generally attacked by treating the waste jointly with sewage or by nutrient fortification.

H. Seeding

When waste stabilization ponds are first placed in operation, there is an initial lag period during which natural seeding occurs and the biota becomes established. Many of the factors that govern the seeding pattern and rate of plankton growth are not understood. So far as raw sewage ponds are concerned, it would seem desirable to initiate operation early in the growing season and to start with a pond containing some water for dilution and seed. Recommendations for cannery lagoon operation stress the desirability of retaining 25 per cent of the lagoon volume when draining, in order to seed and dilute fresh incoming wastes at start of the next campaign (26).

With ponds treating sewage or a nutritionally balanced industrial waste, appearance of the biota is spontaneous and offers no great difficulty. However, when the nature of the waste disqualifies it as a suitable medium for an algal-bacterial association,

special seeding effort must be used. Although considerable laboratory work has been done along this line, field application to ponds has been extremely limited.

In 1951 several Minnesota cannery lagoons were inoculated with a non-sulphur, purple bacterium (Rhodopseudomonas sphaeroides, Van Niel) to investigate earlier observations that a reduction of odor seemed to be correlated with growth of these organisms. Following study it was concluded that they were not the primary cause of odor reduction (39). Simultaneous studies on several cannery lagoons in Wisconsin included inoculation of one lagoon with brewers' yeast (41). No living yeast cells were found thereafter in the lagoon proper, indicating unsuitability of the environment. Seeding has also been investigated in connection with treatment of pulp and paper mill wastes. In ponding studies of kraft-mill wastes (40), storage pond sludge, contents of a cow stomach (rumen), and sludge from a lake were used as seed. Lake mud and stomach content were found to be most effective. Other studies on lagooning of white water (31) showed greatest B.O.D. reduction with a seed-to-feed ratio of 4 to 1 when an undescribed "acclimatized seed" was used.

SUMMARY

Growing popularity of waste stabilization ponds has created new interest in the pond mechanism and factors affecting it. Mode of action and impact of these factors influence design and resulting pond accomplishment.

Of importance are photosynthetic oxygenation; interrelation of light penetration, algal density, and depth; the effect of temperature upon B.O.D. rate, D.O. saturation level, and photosynthesis; and the manner in which seasonal forces are superimposed upon daily fluctuation in pond characteristics. The relative influences of ice cover and loading pattern and the responses that follow have been pointed out.

With nutritionally suitable wastes, a typical biota of algae, bacteria, and other organisms becomes established. Exact biotic character is governed by loading intensity, loading pattern, season, and geography. Thus far, fortification with nutrients and seeding with special organisms have had limited application. As the interplay of these factors becomes better understood, use of waste stabilization ponds will be put on a more rational and efficient basis.

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